Microstructural Development in Friction Welded Aluminum Alloy with Different Alumina Specimen Geometries

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Abstract

Friction welding, one of the most effective, energy- saving processes for solid-state joining of similar and dissimilar materials, holds the advantage of high joint integrity. The friction welding of metal and ceramic gives new possibilities of application due to the fact that both materials have significantly distinguish physical, chemical and mechanical properties. Different specimen geometries (flat, pin and taper pin ceramic faces with flat metal face) of alumina and 6061-aluminum alloy were welded by direct drive friction welding to investigate the effect of joint geometry on microstructural development, microhardness and thermal properties of friction-welded components. The welding process was carried out under different axial pressures and friction times while rotational speed (1250 rpm) and axial force (5000N) were kept constant. The experimental results showed that the shape of ceramic face had a significant effect on the joint structure, microhardness and thermal properties.

Keywords

Alumina; Aluminum Alloy; Friction Welding; Joint Geometries; Microstructure; Vickers Microhardness

Introduction

The use of various materials has significantly increased in many industrial applications. A single material is often not suitable to meet full range of applications, and thus combinations of materials with different properties are generally required. One interesting combination involves joining a metal and a ceramic to combine ductility, high electrical and thermal conductivity with high strength and chemical inertness. Metal/ceramic joints are used in automotive industry, cutting tools, turbine blades and dental implants (Kohnle et al. 2002). Joining ceramics to metallic materials requires careful consideration of several cases originating from the differences in physical and chemical nature of these materials. One of the key points in joining is to form a tight and effective interface that compensates for thermal expansion mismatches between the two constituents (Suganuma 1990; Weiss and Sassani 1998).

Various methods such as brazing, active brazing and diffusion bonding have been used to join ceramics with metals. However, these methods have lower efficiency when compared to friction welding method (Kanayama 1985; Weiss and Sassani 1998; Ahmad Fauzi et al. 2010). The latter has been used as a solid phase welding technique to bond similar or dissimilar metals. The advantages of friction welding include high reproducibility, short production time and low energy input (Yokoyama 2003). Joining dissimilar materials is generally more challenging than that of similar materials due to differences in physical, mechanical and metallurgical properties of the parent materials. It is necessary to produce high quality joints between different materials to fully exploit their properties. The growing availability of new materials and higher material requirements have created a greater demand for joints of dissimilar metals (Satyanarayana et al. 2005).

The friction welding process is a solid state joining process that produces a weld under the compressive force contact of one rotating and one stationary workpiece (Uday et al. 2010). The heat is generated at the weld interface because of the continuous rubbing of contact surfaces, which in turn causes temperature rise and subsequent softening of material. Eventually, the material at the interface starts to flow plastically and forms an upset. When a certain amount of upsetting has occurred, the rotation stops and the compressive force is maintained or slightly increased to consolidate the weld. Friction time, friction pressure and rotation speed are the most important operational parameters in the friction welding process (Sahin 2009; Sunay 2009).

Also, the geometric parameters of the face such as the height and the shape of the pin and the shoulder surface of the head greatly influence the material flow and the heat generation due to friction forces (Buffa 2006). Similarly, pressure applied during the welding has to be carefully chosen since the pressure generated on the surface and under the pin end determines the heat generated during the process. The rotation speed and the time rate also need to be appropriately selected in order to improve cohesion that results in proper microstructure development and eventually good strength and efficient welding of the joint (Boz and Kurt 2004; Zhao 2005; Scialpi, De Filippis et al. 2007).

In this study, experimental work was carried out to study the effect of joint geometry on microstructure of friction welding for sintered alumina rods and commercial 6061-aluminum alloy. Two bars with equal or different ceramic shapes were welded at different operating parameters using the same set up. The specimens were rotated at a constant rotational speed of 1250 rpm and an axial force of 5000 N, at various axial pressures and the times. The mechanical properties of the joints were determined by microhardness tests, and results were compared with those produced in the previous papers.

Material and methods

Materials

The materials to be joined are sintered alumina rods (99.4Al_2O_3, 0.33SiO_2, 0.11Na_2O, 0.024CaO, 0.081Fe_2O_3, 0.014NiO, wt %) and commercial 6061 aluminum alloy rods (96Al, 2.1Si, 0.95Mg, 0.33Fe, 0.17Cu, 0.066Cr, 0.04Mn, 0.022Ti, 0,014Zn, 0.014Ni, 0.013Ga). Both of these materials are typically used in aerospace applications. The starting materials are alumina commercial powder supplied by Maju Santifik Sdn Bhd (high purity 99.4%, average particle size 1.04 μm) and the aluminum alloy rods supplied by a local supplier (Heap Sing Huat Metal and Machinery Sdn Bhd). Tests were conducted on the welded joints produced by friction welding of 16 mm diameter sintered alumina rods and the aluminum alloy. The joints were formed using direct drive friction-welding machine modified from an existing lathe machine model APA TUM-35. The dimensions and shapes of the specimens used for friction welding are shown in Fig. 1. The details of the specimens are also listed in Table 1.

The alumina rods were prepared through slip casting in plaster of Paris molds. The green cast alumina rods were then sintered at 1600°C for soaking time of 5 hrs. The average bulk density of alumina sample was 3.7961 g/cm^3. On the other hand, the aluminum rods samples were cut off from a large 6061 Al alloy block and then machined down to the diameter of 16 mm required using a lathe machine. The end surfaces of alumina and aluminum alloy rods were smoothened and any sharp edges were removed. The specimens were then placed in a container filled with acetone and the grease on the specimens was cleaned by an ultrasonic bath.

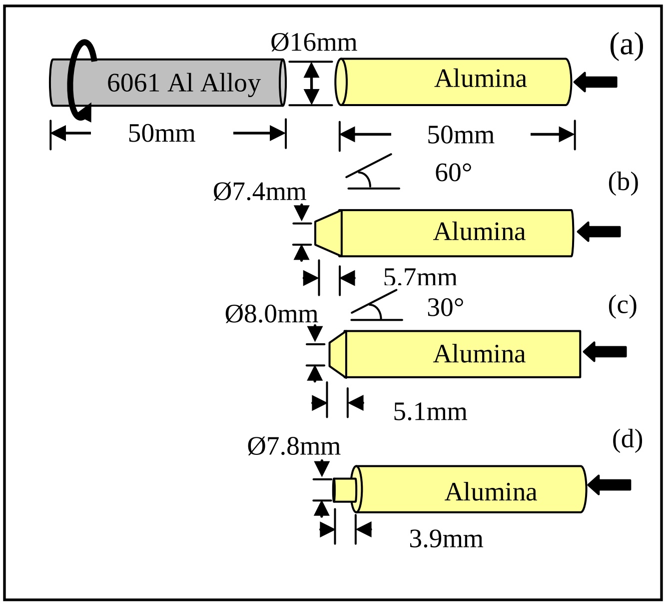

FIG. 1 THE SIZE OF SPECIMENS FOR (a) FLAT CERAMIC FACE TO FLAT METAL FACE , (b) TAPER PIN ANGLE 60° CERAMIC FACE TO FLAT METAL FACE, (c) TAPER PIN ANGLE 30° CERAMIC FACE TO FLAT METAL FACE, (d) PIN CERAMIC FACE TO FLAT METAL FACE.

TABLE 1 THE DIMENSIONS OF THE FOUR CERAMIC SPECIMENS USED FOR FRICTION WELDING

No.	Description of the ceramic shape	Big diameter of the ceramic shape	Small diameter of the ceramic shape	Pitch of the ceramic shape
1	Flat	16 mm	16 mm	none
2	Taper pin 60	16 mm	7.4 mm	5.7 mm
3	Taper pin 30	16 mm	8 mm	5.1 mm
4	Pin	16 mm	7.8 mm	3.9 mm

Friction Welding And Test Specimens

The direct drive friction-welding machine used in the present study was equipped with peripheral devices for the measurement of test conditions (friction pressure, time and rotational speed), as well as a stabilizer to measure the stability of the device during the testing.

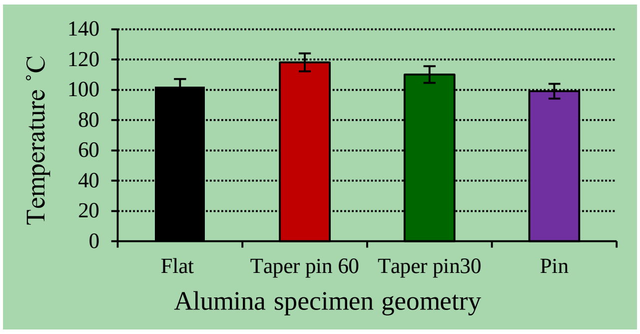

FIG. 2 EFFECT OF JOINT GEOMETRY ON THE FRICTION-WELDED TEMPERATURE OF THE JOINING BETWEEN PURE ALUMINA AND 6061 AL ALLOY JOINED AT 1250 RPM

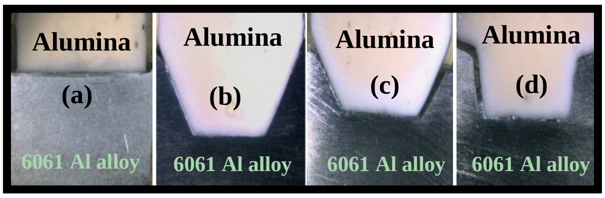

FIG. 3 MICRO CROSS-SECTION VIEWS OF FRICTION ZONE WELDED BY, (a) FLAT CERAMIC FACE TO FLAT METAL FACE, (b) TAPER PIN ANGLE 60° CERAMIC FACE TO FLAT METAL FACE, (c) TAPER PIN ANGLE 30° CERAMIC FACE TO FLAT METAL FACE, (d) PIN CERAMIC FACE TO FLAT METAL FACE.

TABLE 2 THE PARAMETERS USED FOR THE EXPERIMENTS

No.	Description of the ceramic shape	Small diameter of the ceramic shape	Area of the surface R2*π (mm^2)	Axial force (N)	Axial Pressure (MPa)	Friction time (Sec)
1	Flat	16 mm	200.96	5000	25	20
2	Taper pin 60	7.4 mm	42.99	5000	116	45
3	Taper pin 30	8 mm	50.24	5000	100	40
4	Pin	7.8 mm	47.76	5000	105	25

The various friction welding workpiece pairs are shown in Fig. 1. The aluminum alloy rod had flat polished surfaces while alumina ceramic rods had different shapes. The friction welding was performed with the different shapes of alumina to the aluminum rod. The applied pressures and friction times in this study were shown in Table 2. Forging pressure (30 MPa), forging time (40 sec) and rotational speed (1250 rpm) were kept constant all through the experiment. The values of these parameters were obtained after trial and error experimentation (Table 2). Five welds were performed for every set of mechanical test in order to ensure accuracy and repeatability of the results. Primary factors were selected based on the previous studies (Ahmad Fauzi 2010; Uday 2011). The welded specimens were then sectioned at the weld joint to study the microstructure of the welding zone. The microstructure was observed by using an optical microscope and an emission scanning electron microscope (FESEM). Vickers microhardness across the interfaces and friction temperature were also investigated.

Results and Discussion

Variation of Friction Temperature with Respect to Joint Geometries

The values of temperatures obtained from the results of temperature measurements of friction welding of pure alumina with 6061 Al alloy for the different joint geometries friction welding at 1250 rpm are given in Fig. 2. The measurements were performed using Digital Thermometer (Ebro TFN 520/530, Produktions- u. Vertriebs GmbH, Germany) based on the standard DIN IEC 584-2 for accuracy of probe (Uday et al. 2012). Generally, it can be observed that shapes having smaller contact area (pin and taper pin 30°) led to high temperature rise. The smaller area was attributed to smaller contact for friction. As expected, welding with the flat shape having a higher diameter showed the lower temperature. In addition, a reduction in temperature was observed in the case of the shape with pin. However, in some cases especially in the pure alumina, the temperature increased in taper pin 60°, probably as a result of the presence of a large penetration into the metal.

Effect of the Joint Geometry on the Microstructure of the Weld

The geometry of the joint would highly influence the process development and plays a critical role in material flow which in turn governs the traverse rate at which friction welding could be conducted (Mishra and Ma 2005). Fig. 3 (a-d) shows the cross-section of the pure alumina and 6061-aluminum alloy welded joint at various geometries of ceramic face. It can be observed that a good interface appearance was obtained by using flat shape (Fig. 3a) and taper pin 60˚ shape (Fig. 3b). In these two geometries, the weld finishing was clean and no obvious defects were found. However, when welded by taper pin 30º and pin shapes, a lack of contact between the ceramic and the metal surfaces was observed (Fig. 3 c, d). The taper pin 30º and pin shape joints endured more resistance to welding than the other two shapes in the friction welding process. Subsequently, the latter two developed lower mechanical strength.

Optical microscopy examinations were used to study the influence of the ceramic shape geometry on the microstructure of the friction-welding joint. Figs. 4-6

show the microstructure of the joined specimens involving the various regions of the flat, taper pin 30° and pin shapes of the composites. The extent of deformation experienced by the metal and the flow of the materials was dependent on the amount of heat generated and the shape of the ceramic face (Zhao 2005; Zhang et al. 2006). It was observed in this study that the microstructure was affected greatly by the flat shape geometry affected at 1250 rpm; and a more refined grain structure was developed at the joints. The deformation zone (darker shade) had clearly formed between the two welded pieces as shown in Fig. 4. The effect of rotation of the specimen could be seen in this type of ceramic face. When the grains were pulled in the direction of rotation, they were subjected to torque at high friction temperature. Although the observations were made on good weld surface, however, visible defect was found in the joints of taper pin 30° and pin shapes (Fig. 5 and 6). Thus, it was shown that with the latter two type shapes could not produce good joints. From Fig. 5 the aluminum alloy side showed severe plastic deformation and effect of frictional heat (indicated by damaged piece surface of the metal alloy) near the weld zone, while Fig. 6A shows that the heat affected region was heterogeneous in the pin shape. As the head of the pin shape being smaller, there would be intense heat at point of contacts or weld, resulting in a non-uniform heat distribution at the surface and around pin head, thus forming non-uniform layers of the phase formed (Fig. 6 A and B). The size of the grains after that changed gradually to undeformed zone as shown Fig. 6C.

For the cross-section of the taper pin 60° shape, the joint was divided into three different regions at the weld interface, i.e. the unaffected zone (UZ), deformed zone (DZ) and the transformed and recrystallized fully deformed zone (FPDZ). These microstructures revealed that different zones along the cross section of the weld experienced different thermal and pressure force effects. The formation of the three zones is in agreement with other researchers (Lin et al. 1999; Özdemir 2005; Avinash et al. 2007; Özdemir et al. 2007; Sathiya et al. 2008). Fig. 7 shows the microstructures in the deformation zone welded by taper pin 60° shape. The interface region experienced high temperature and an extensive plastic deformation characterized with dynamically recrystallized grains. The metallic material deformation and the flow of the materials were related to the microstructure and the properties of the interface. The taper pin 60° shape geometry highly affected the deformation of microstructures.

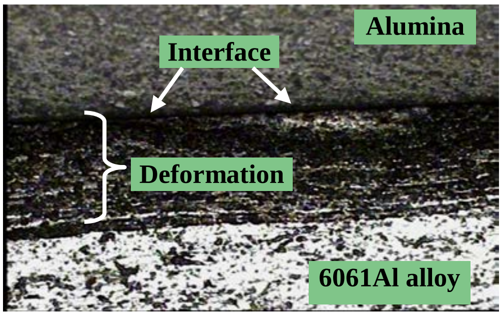

FIG. 4 MICROSTRUCTURES OF FRICTION WELDED BETWEEN ALUMINA AND 6061 ALUMINUM ALLOY FLAT SHAPE AT 50X

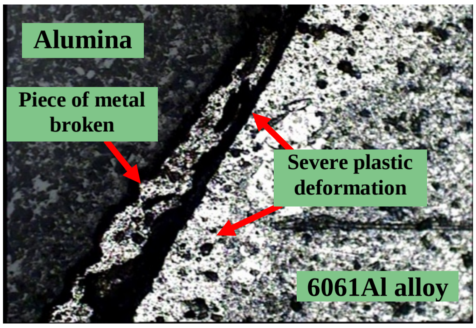

FIG. 5 MICROSTRUCTURES OF FRICTION WELDED BETWEEN ALUMINA AND 6061 ALUMINUM ALLOY WITH TAPER PIN ANGLE 30° AT 50X

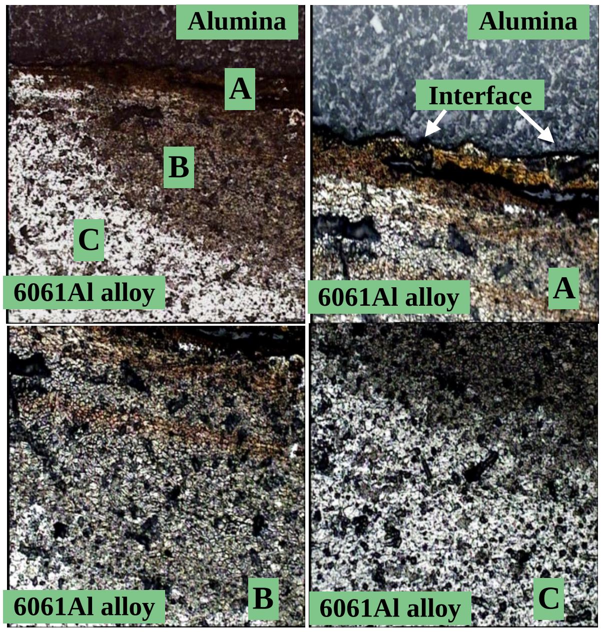

FIG.6 MICROSTRUCTURES OF FRICTION WELDED BETWEEN ALUMINA AND 6061 ALUMINUM ALLOY WITH PIN SHAPE (50X), (A) FULLY DEFORMED ZONE (100X), (B) DEFORMED ZONE (100X) AND (C) UNDEFORMED ZONE(100X)

Friction welding gave rise to a noticeable microstructural changes. The optical micrograph revealed that the deformation in FPDZ resulted in severe deformation of the grain structure (Fig. 7A). In this zone, the grain, shape and the dimensions evolution were unclear. This transition zone corresponded approximately to the edge of welded ceramic face. In this zone, recrystallization happened

close to the joint in the deformation zone.

Fine grain structure was observed in the DZ welded by taper pin 60˚ shape while the size of the grains was small than that of the other regions (Fig. 7B). The size of the grains changed gradually from FPDZ to UZ region as shown Fig. 7C. In the welding process, the deformed grains experienced high temperature and violent plastic distortion and after dynamically recrystallized, the grains of different sizes were formed. It can be found that welding by taper pin 60˚ shape produced desirable weld joints. The microstructure in the interface and the deformation zone realized smooth transfer without obvious defects.

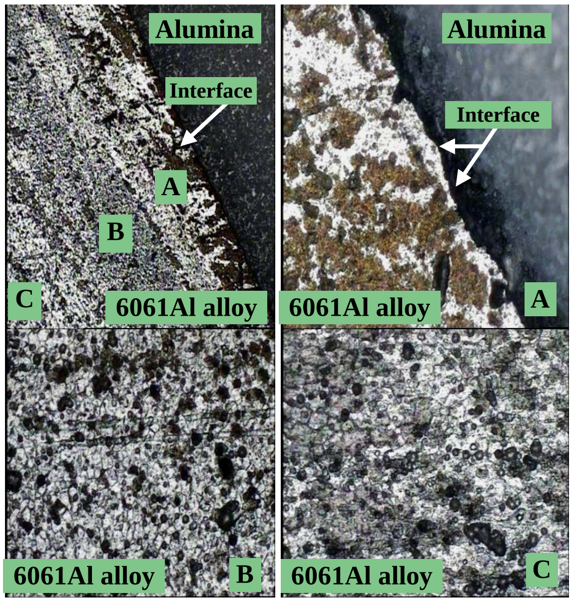

FIG.7 OPTICAL IMAGES OF INTERFACE PROPERTIES OF THE TAPER PIN 60° SPACEMEN IN THE WELD DEFORMATION ZONE (50X), (A) FULLY DEFORMED ZONE (100X), (B) DEFORMED ZONE (100X) AND (C) UNDEFORMED ZONE (100X)

The interface region between the two material joints was also examined using FESEM. Fig. 8(a-c) shows the grain size distribution of the different zones in the metal side. It revealed that the deformation zone welded by taper pin 60º shape exhibited a non-uniform size distribution and was concentrated at the interfaces between finer and coarse grains as a result of distortion in the metal. Fig. 8a shows the microstructure of FPDZ near the interface where it was divided into two regions. The grain boundaries did not clearly appear in one of them while the other showed a gradual increase in the grain size (Fig. 8b). Finer grain structure was observed in the FPDZ at the nearby interface. The DZ observed coarser grain size than FPDZ as shown in Fig. 8c. The microstructure of the UZ is presented in Fig.8c where the grain size was observed to be elongated and parallel to the interface similarly reported by Sathiya et al. 2008.

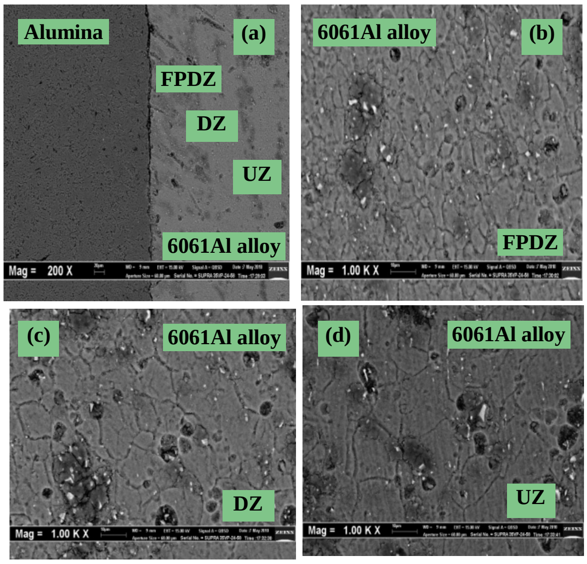

FIG. 8 (A) GRAIN STRUCTURE DISTRIBUTION EXHIBITED WITHIN THE THREE DIFFERENT ZONES AT THE FRICTION WELD INTERFACE BETWEEN ALUMINA AND 6061 ALUMINUM ALLOY, (B) RECRYSTALLIZED FULLY DEFORMED ZONE (FPDZ), (C) DEFORMED ZONE (DZ) AND (D) UNAFFECTED ZONE (UZ)

Vickers Microhardness Tests

The hardness variation across the zone of joining is an important factor that dictates the mechanical properties of the joints. The deformed microstructure causes a large decrease in the grain size which could lead to hardening in the interface region (Yilmaz et al. 2002; Sathiya et al. 2007). The mechanical properties vary according to the variations in the hardness across the joint zone (Sathiya et al. 2008). In this study, the microhardness values were taken at the center of the metal alloy side, the weld interface (Zero point) and the ceramic side with the distance of 1 mm on either side and across the joint zone (Fig. 9). In this study where the geometry of the joints were considered, it could be seen that the microhardness of 6061 aluminum alloy was generally lower with less scatter than that of the pure alumina ceramic. The hardness in the aluminum alloy was the highest near the interface. On the other hand, it could clearly be seen that the hardness of ceramic varied greatly, i.e. it showed a wide scatter. As explained earlier, this is attributed to the flaws present on the sintered rods, typically large pores. At the interface of pure alumina joint with aluminum alloy, however, the taper pin 60° shape gave maximum hardness values (Fig. 9). The increasing hardness in the welding interface was associated to the microstructure formed at the

interface as a result of the degree of heat flow input, axial pressure and plastic deformation. In general, the increase in the hardness of the aluminum alloy near the interface could be related directly to the high deformation and temperature hardening in the ceramic shape.

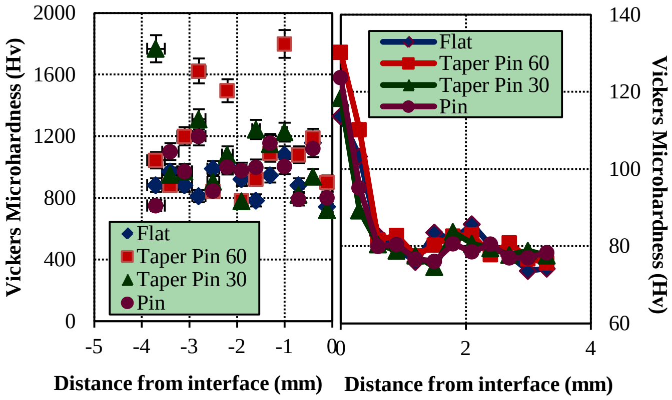

FIG. 9 MICROHARDNESS TRAVERSE OF 6061 AL ALLOY-ALUMINA FRICTION WELDED JOINTS WITH DIFFERENT CERAMIC SHAPES (A) CERAMIC SIDE, (B) METAL SIDE

Conclusion

In this study, alumina-6061 aluminum alloy joints were welded successfully using friction welding. Four different ceramic face geometries were designed to investigate the effect of the shape of ceramic faces on the microstructure of the 6061 aluminum alloy. The results indicated that the shape of the ceramic face had a significant effect on the joint structure and mechanical properties of aluminum alloy. The ceramic face strongly affected the flow of metal. Good weld was acquired using the taper pin 60º shape. The appearance of the weld was clean without obvious defects. The extent of metal deformation and the flow of materials depended on the amount of heat generated as well as the form of the ceramic face connected to the metal surface. The hardness variation across the joint zone is an important factor which dictates the mechanical properties of joints. The microhardness traverses could not adequately describe the properties of the alumina in the joints. This was attributed to flaws particularly the large pores in the sintered alumina. Increasing hardness in the welding interface was related to the microstructures formed in the welding interface as a result of the degree of heat input and plastic deformation. The deformation decreased the grain size which led to hardening in the region of the interface. Hence, at the interface, a taper pin 60° shape gave the highest hardness.

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